High Field Magnet R&D Program A view from CERN

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With many contributions from CERN TE-MSC and FCC collaborators

US-MDP Workshop Washington, DC
4-5 December 2019

Outline

- The nature of the program
- The leading questions for the R&D
- The R&D lines responding to the questions
- The R&D vehicles
- Deliverables and timeline
- Summary

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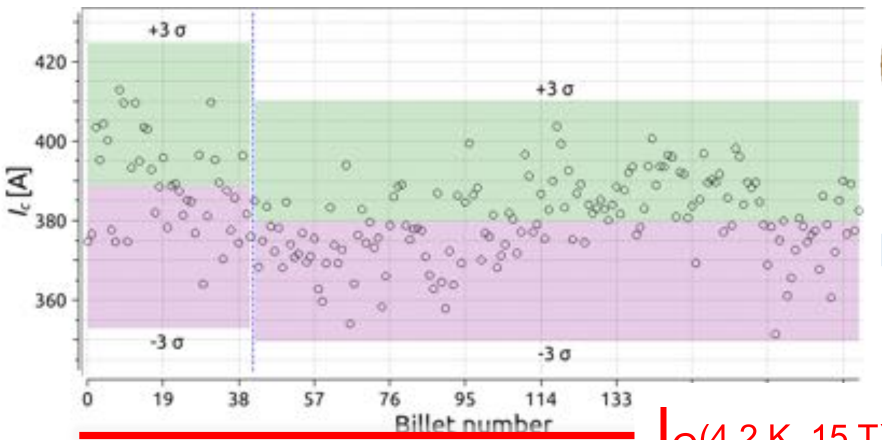
A program responding to demands

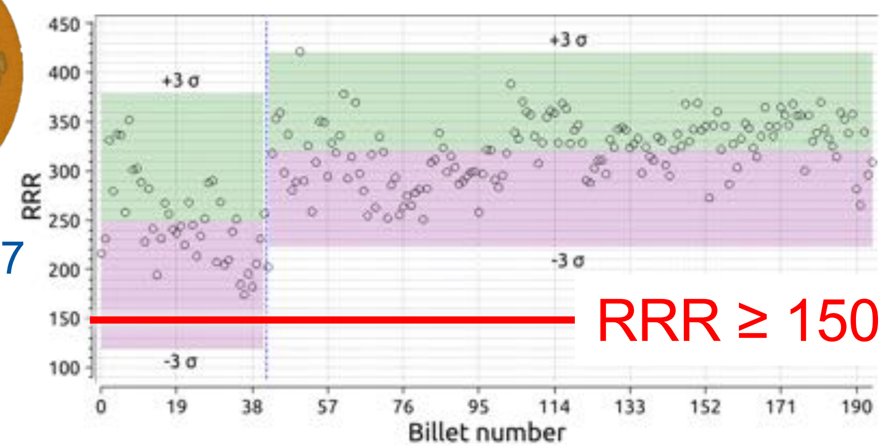
- FCC-hh, including the specific demands from HE-LHC, has been **the main driver of the development of HFM**
  - We have shown that a field of 16 T can be generated by Nb_3Sn (RMC-03, 2015)
  - We have produced 14.6 T in a 100 mm aperture (FRESCA2, 2018) and 14.1 T in a 60 mm aperture (US-MDP CT1 2019)
  - We have demonstrated that the J_C target of 1500 A/mm^2 at 16 T and 4.2 K is within reach (2018, 2019), and we have two additional potential suppliers of HL-LHC class wire (TVEL, JASTEC)
- All of the above **in collaboration** with the whole-world community
- The HFM development activities have been **instrumental to HL-LHC**, and in particular the success of the 11T MBH long magnet

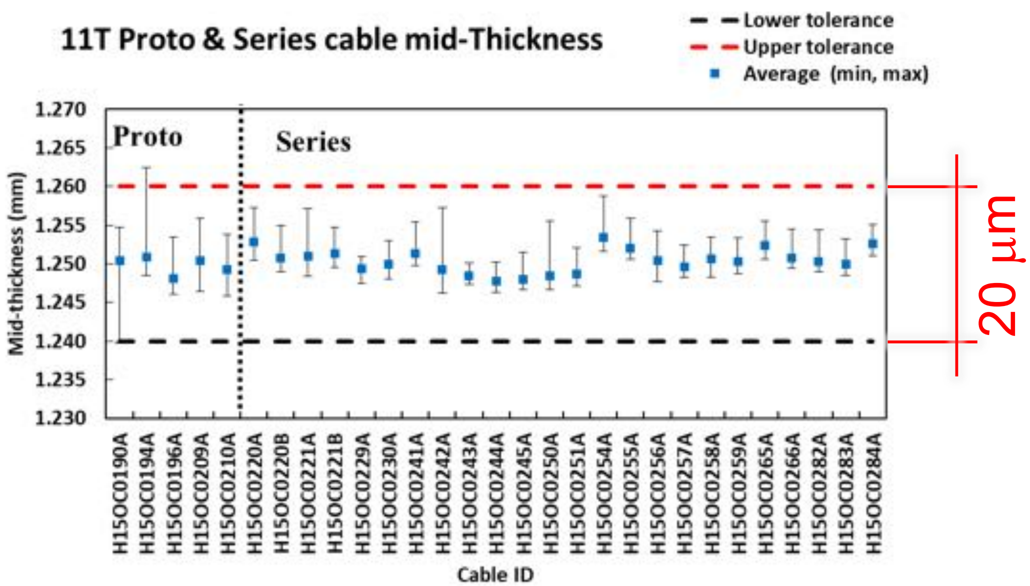
CERN has completed the production of the first accelerator Nb_3Sn dipole magnet, **an historical milestone for accelerator technology**.

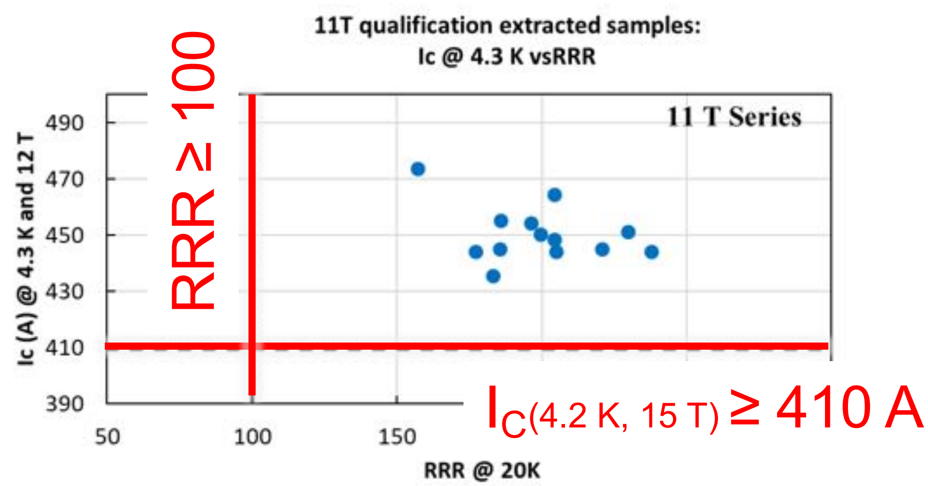
HL-LHC wires and cables



RRP 108/127

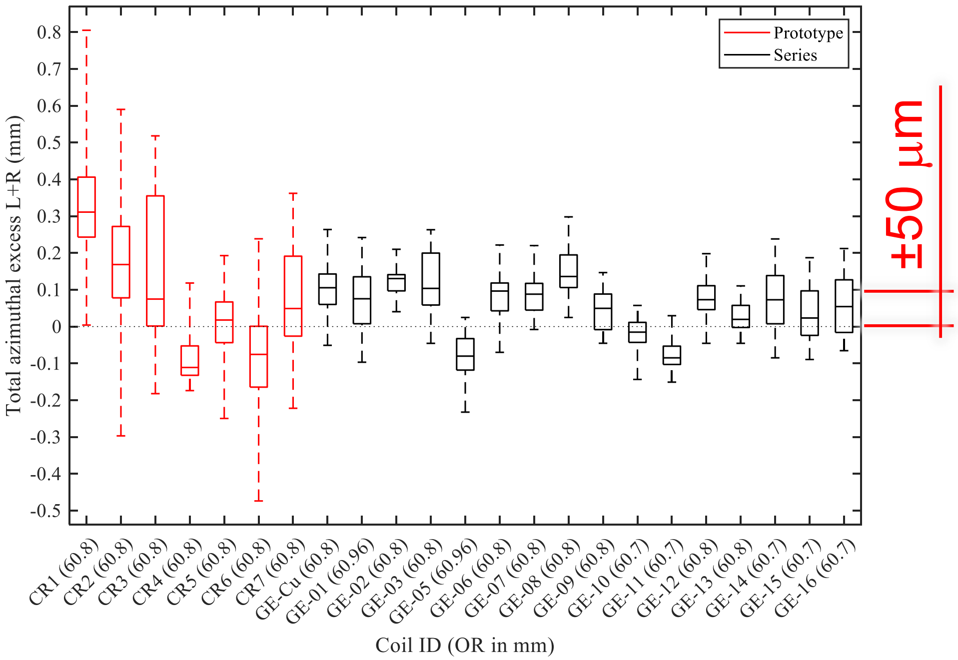


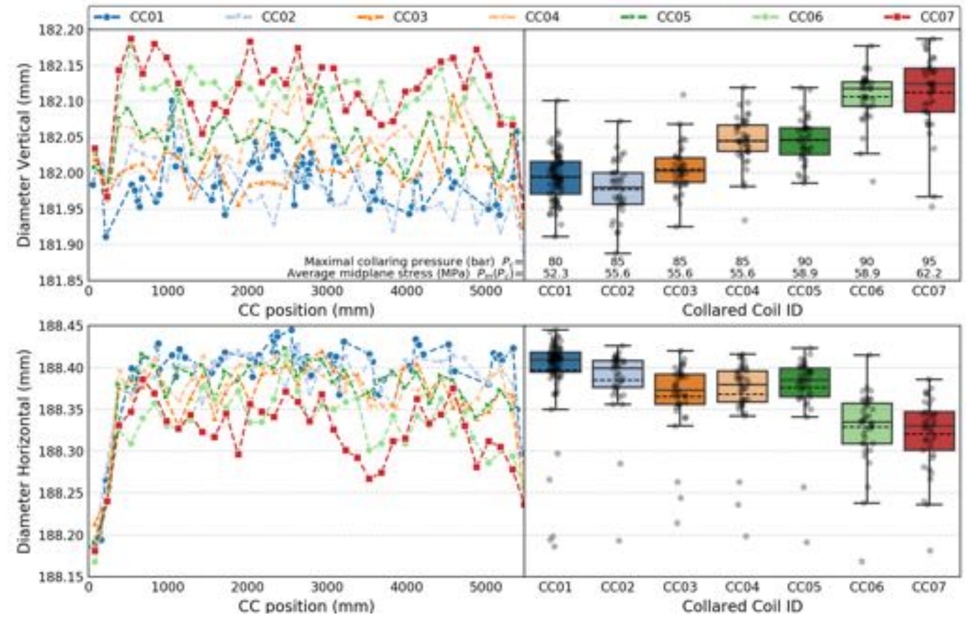


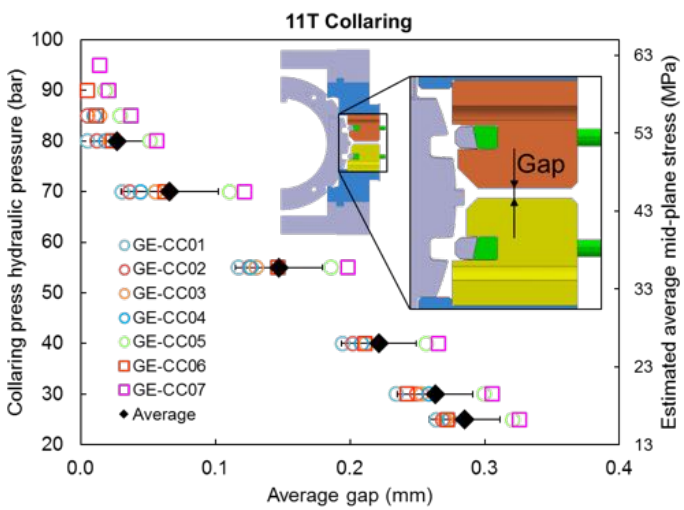


This is an industrial production !

11T collared coils



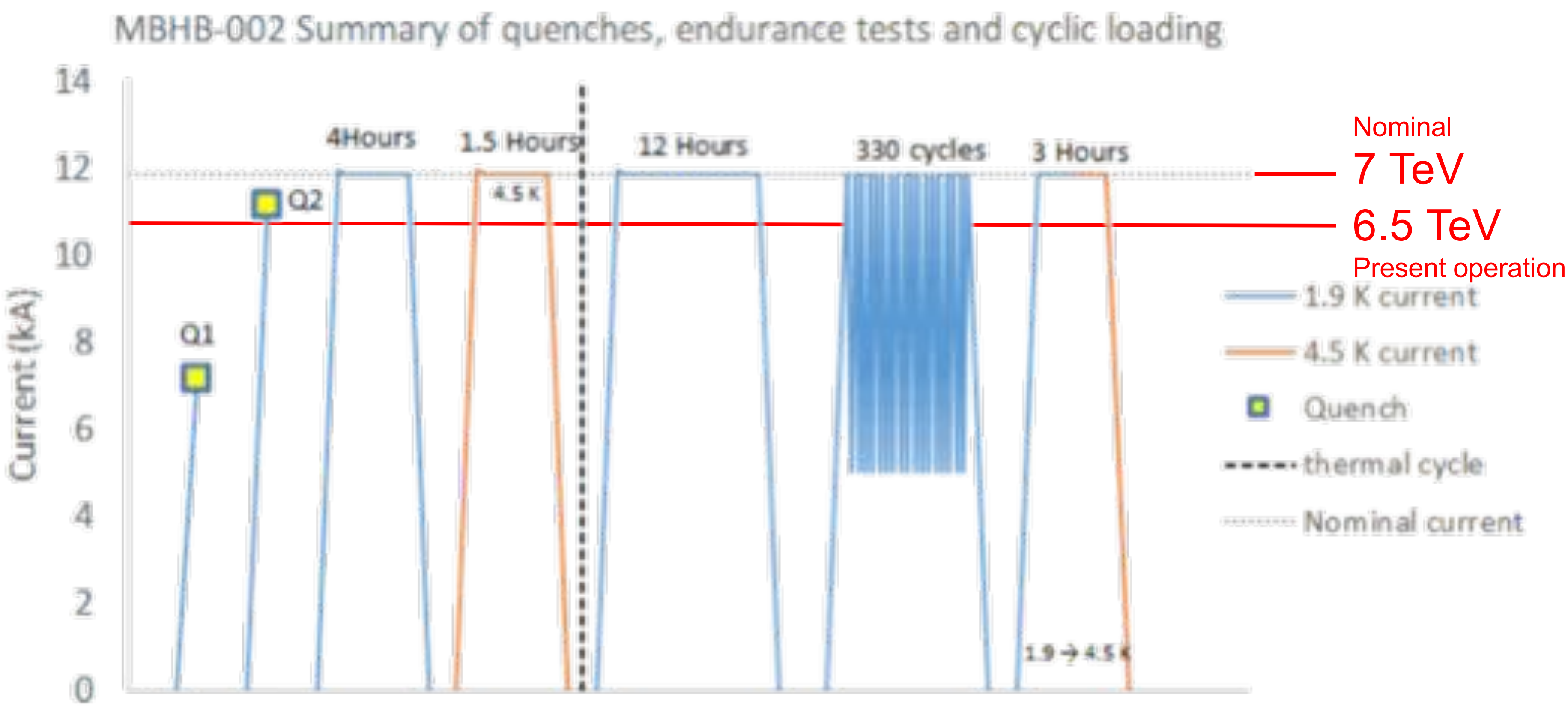


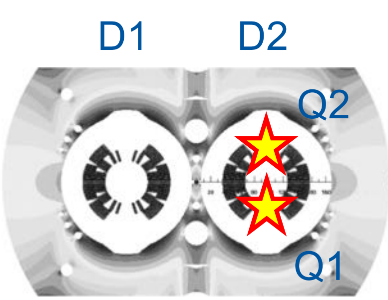


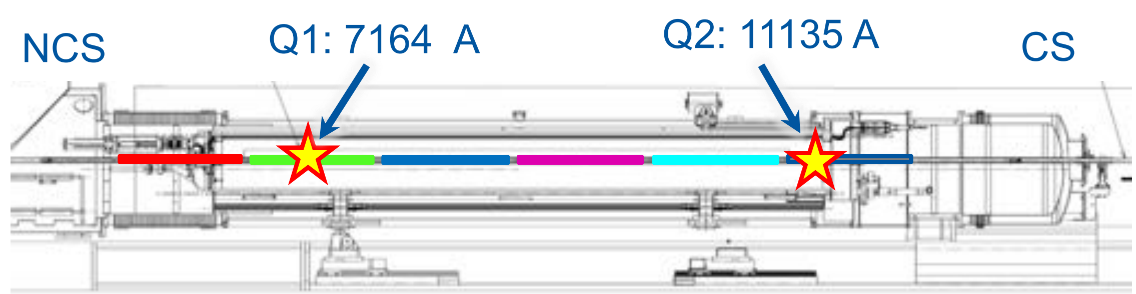
This is an industrial production !

LMBHB0002

LMBHB002 powering tests



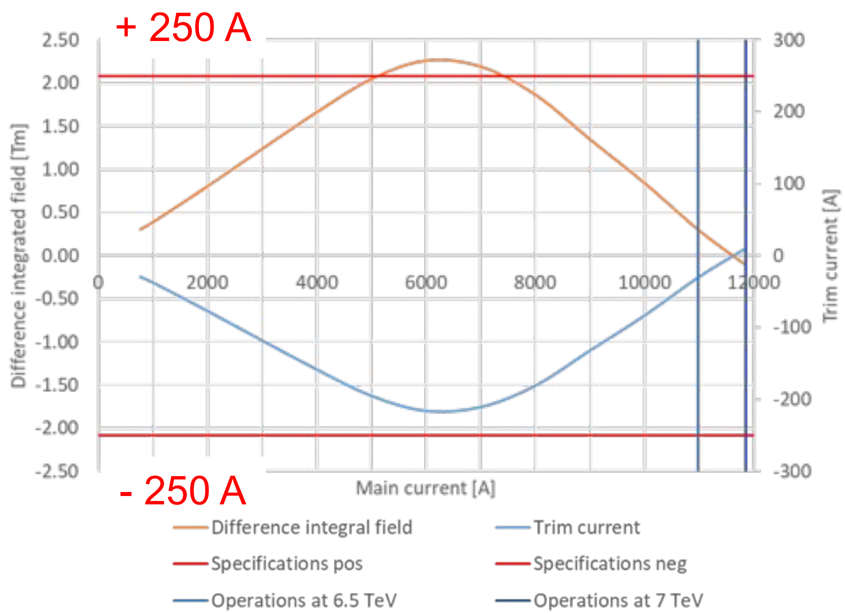




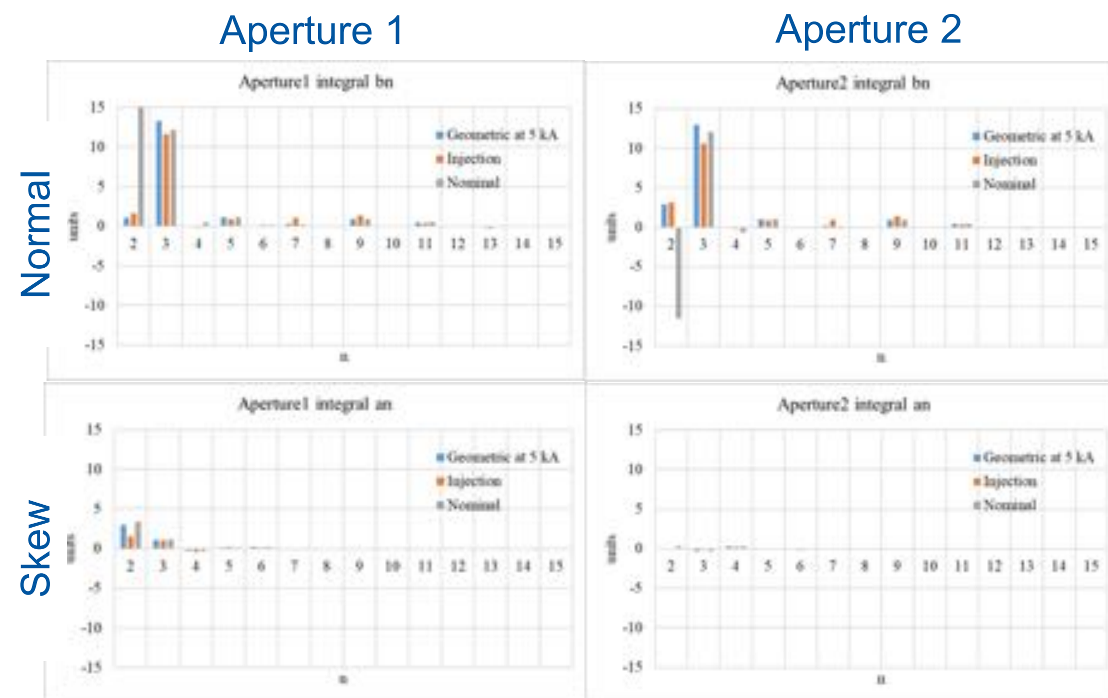
This is an accelerator worthy dipole !

LMBHB002 Field Quality

Transfer Function difference MB vs. MBH



Geometric Multipoles (@17 mm)



A trim current is injected in the 11 T dipole circuit to match LHC dipole transfer function (based on average of integral field measurements for the 2 apertures)

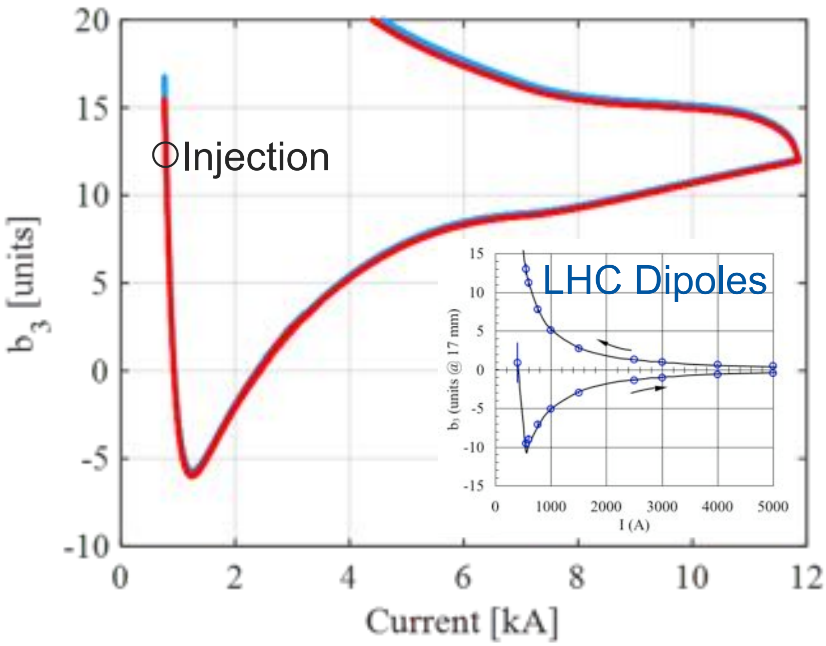
b_2 (normal quadrupole) arises from iron saturation and is as expected (~±14 u);

b_3 (normal sextupole) is a bit larger than expected (~7 u).

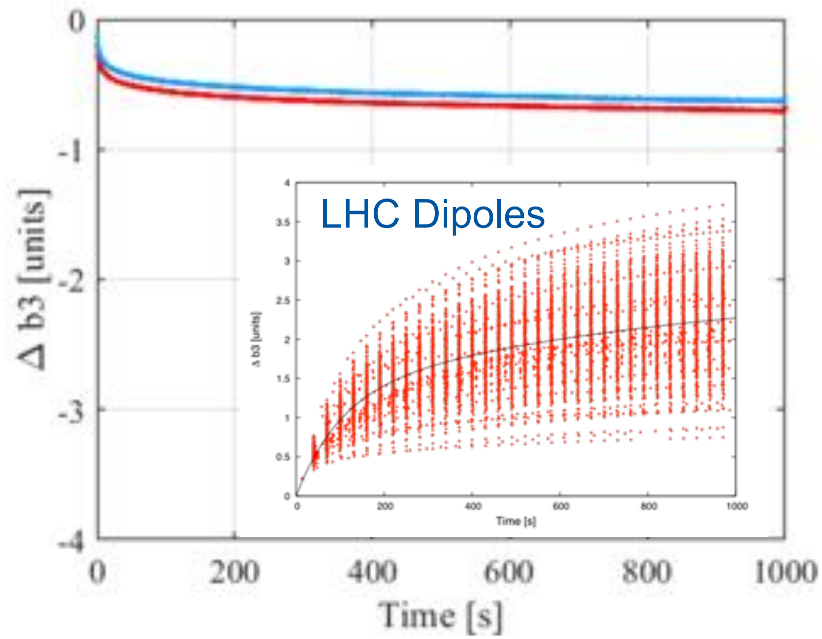
This is an accelerator worthy dipole !

LMBHB002 Field Quality

Persistent Magnetization Currents
(2nd cycle, both apertures)



Time decay at Injection (760 A)



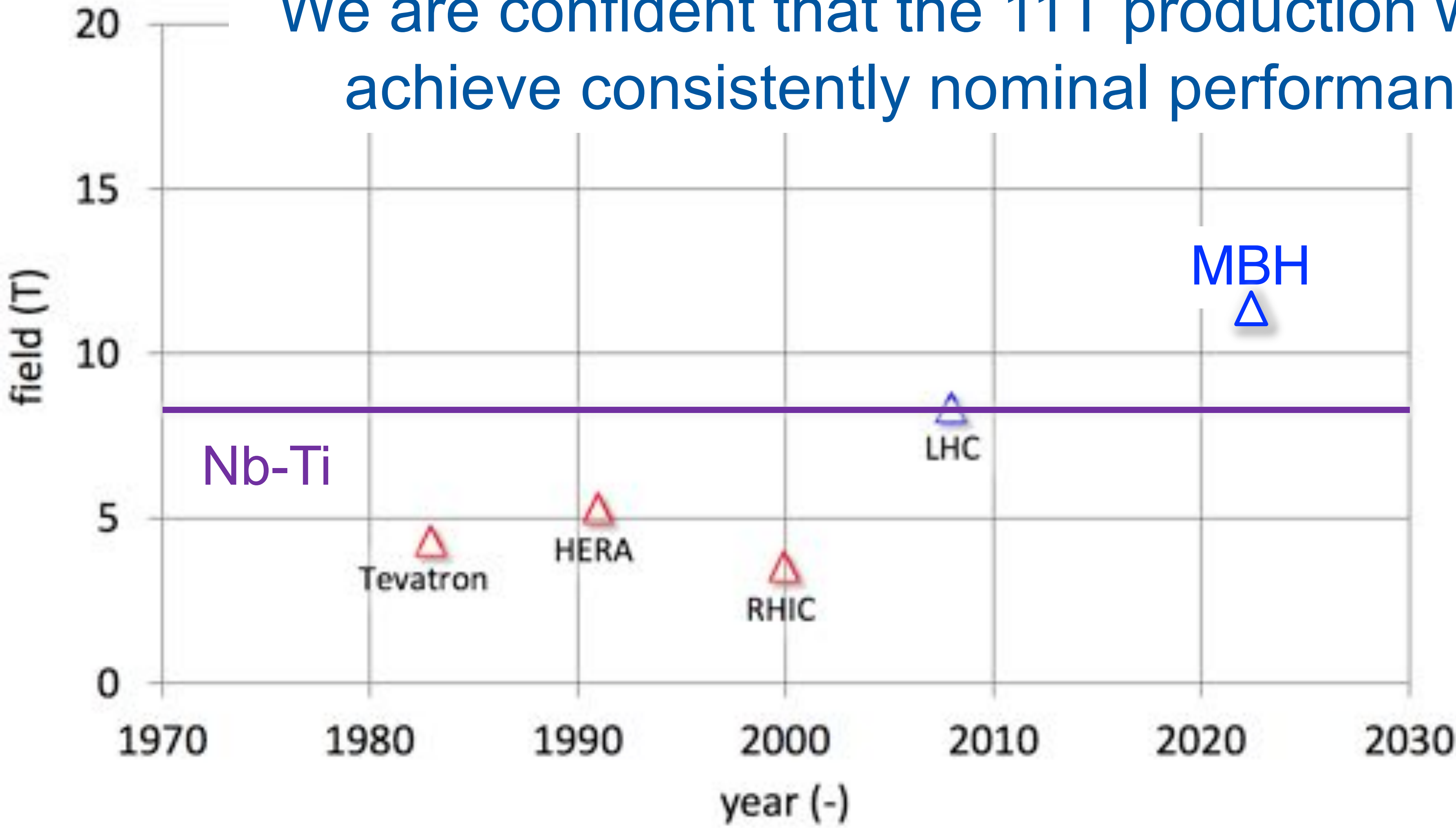
The injection current is on the "wrong side" of the peak of persistent current sextupole due to the inherent magnetic moment of the SC filaments (approximately 50 μm diameter), and ≈ 2.5 times larger than in the LHC Nb-Ti dipoles

b_3 time decay at injection is "reversed" due to the initial point, and relatively small when compared to the LHC Nb-Ti dipoles

This is an accelerator worthy dipole !

HL-LHC 11T significance

We are confident that the 11T production will achieve consistently nominal performance



The 11T MBH is a technology breakthrough !

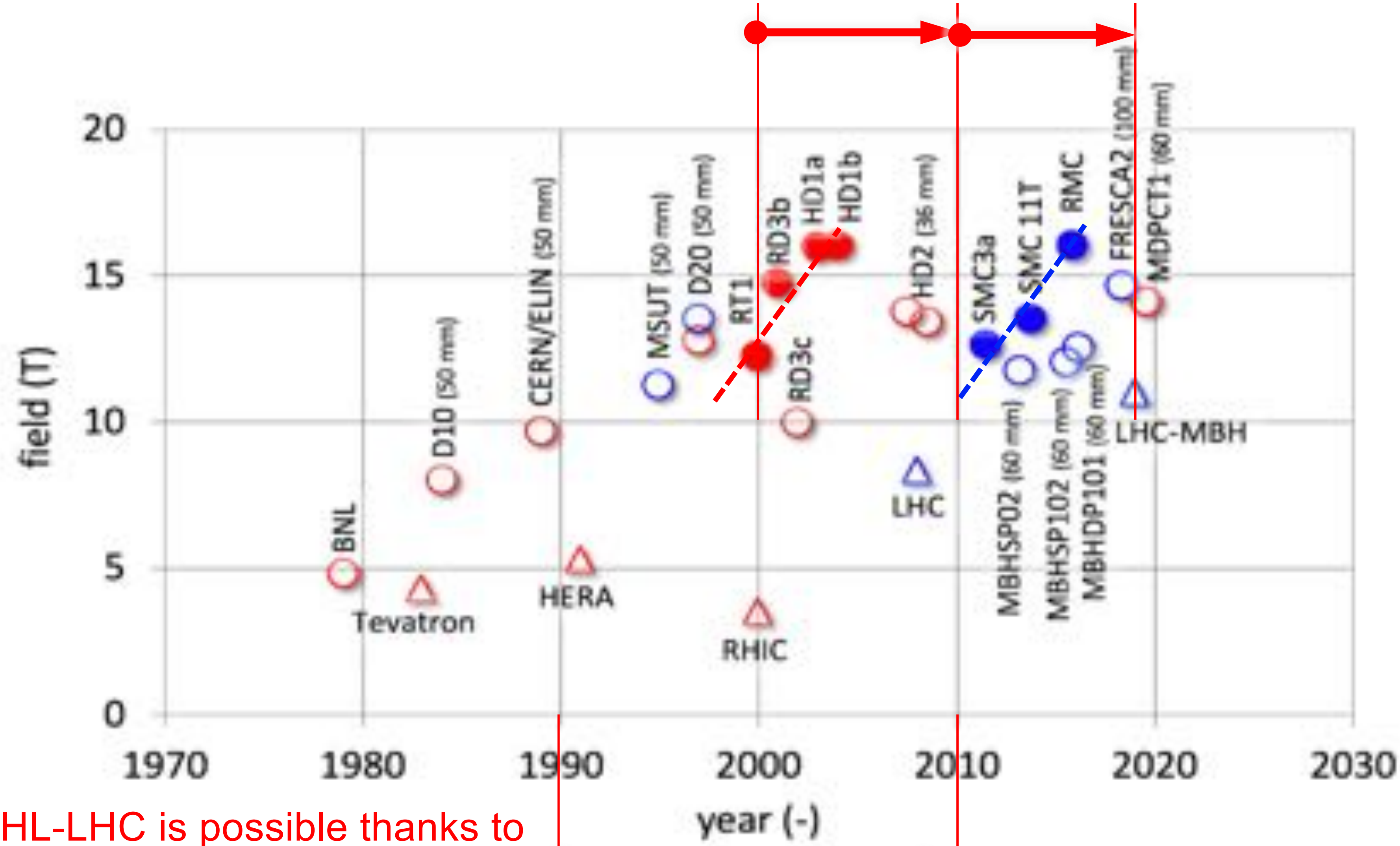
A program for the long term

- The long and winding road of 11 T has reminded us that **there is a long way from demonstrators to model, prototype magnets, pre-series and industrial production.** We need continuity, because:
    - **Lead times for the development of high-field magnets are long**, a typical cycle lasts ten years. Another ten years will be required for industrialization (see later). Not pursuing technology R&D in-synch with HEP scoping studies of new accelerators may result in <u>missed opportunities.</u>
    - Development of high-field superconducting magnet technology requires **infrastructure of large size and cost**. A program that requires such infrastructure is <u>most profitable if pursued with continuity</u>, rather than executed in bursts.
    - High-field superconducting accelerator magnet development relies on many fields of science and engineering, i.e. **a team that is assembled in collaboration with organizations**. Such research team also <u>operates most effectively in a continuous mode</u>

Cycle time

It took ≈ 10 years to establish Nb_3Sn magnet technology

It took ≈ 10 years to make Nb_3Sn accelerator magnets



HL-LHC is possible thanks to ≈ 20 years of Nb_3Sn R&D

A program in collaboration

- This is a proposal for a **collaborative program.** We wish to profit from the competences developed and the team built over the last 15 years (EU-FP6 CARE and NED-JRA, EU-FP7 EuCARD and EuCARD2, EU-H2020 ARIES), and boosted by the FCC activities (EU-H2020 EuroCirCol)
- Today, collaborators have key roles in:
  - Conductor development and characterization (FCC Conductor Development Program)
  - Develop, demonstrate and decide the technology suitable for future accelerator magnets (model developments at CEA, INFN, CIEMAT, CHART/PSI)
- CERN is also a collaborator

What is next ?

- **The HL-LHC Nb3Sn program has set a new benchmark**: we have completed the initial model and prototype magnet development for operation in the 11-12 T field range and the next step is to capitalize on it, **use this benchmark to develop industrial, robust and efficient techniques**.
- We have a few demonstrators showing that Nb3Sn has the potential to operate at fields beyond 14 T, the next step is to **confirm this potential with model magnets and prototypes**.
- We have not yet had the opportunity to explore the potentials of HTS, the next step is to **develop demonstrators to assess this technology**.

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The "leading questions" – 1/3

- Q1: What are the **performance limits** of Nb_3Sn ?
  - Is the target of 16T for accelerator magnets realistic ?
- Q2: Can we improve **training** of Nb_3Sn magnets ?
- Q3: How do we manage the **forces and stresses** in a high-field Nb_3Sn accelerator magnet ?
- Q4: How do we **protect** a high-field Nb_3Sn accelerator magnet ?
- Q5: Can we improve the design and manufacturing processes to **achieve robustness, reduce risk, increase efficiency and decrease cost** as required by a large-scale industrial production ?

The “leading questions” – 2/3

- Q6: What is the potential of HTS materials to **extend the performance reach** of high-field superconducting accelerator magnets ?
  - Basic material and conductor properties
- Q7: Are HTS conductors, cables, coils **suitable** for accelerator magnet applications ?
  - Cable concept
  - Field quality
- Q8: What **engineering** solutions are required to build such magnets, including consideration of material and manufacturing **cost** ?
  - Winding and mechanics
  - Quench detection and protection
  - Splice and joint technology
  - Insulation and impregnation

The “leading questions” – 3/3

- Q9: What is the specific **infrastructure** required for this conductor and magnet R&D, production and test ?

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From leading questions to R&D lines

- R&D-1: Nb_3Sn **conductor** research and development
- R&D-2: Nb_3Sn **magnet technology** research and development, exploring performance limits
- R&D-3: Nb_3Sn **accelerator magnet** development for robust and cost-effective industrial production at large scale
- R&D-4: HTS **material, conductor and coil technology and accelerator magnet** research and development
  - R&D-4.1: Review engineering specifications for HTS conductor (wires, tapes and cables) and pursue the ensuing development
  - R&D-4.2: Develop HTS coil and magnet technology in the form of small-scale demonstrators
- R&D-5: **Insulating materials**, polymers and composites.
- R&D-6: **Infrastructure** for development, manufacture, test and measurement.

LTS (Nb_3Sn) development matrix

		Q1: Performance limits of Nb_3Sn	Q2: Training origins and cures	Q3: Mechanics	Q4: Protection	Q5: Production robustness, risk, cost
R&D-1: Wire and conductor R&D						
R&D-2: Magnet technology	SMC					
	eRMC/RMM					
	Models					
R&D-3: Accelerator magnet development (VE)						

HTS development matrix

		Basic conductor properties (Ic(B,T,α,ε), RRR, k, M, R, …)	Cable concept (stacks, Roebel, transposition, defects, current sharing…)	Splice and joint technology	Insulation / impregnation	Quench detection and protection	Winding and mechanics	Field quality
		Q1	Q2	Q3				Q2
R&D-4.1: Conductor R&D	Tape/Wire							
	Cables							
	Joints							
R&D-4.2: Magnet technology	Small coils (I, PI, NI)							
	Demo coils							

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R&D Vehicles – overview

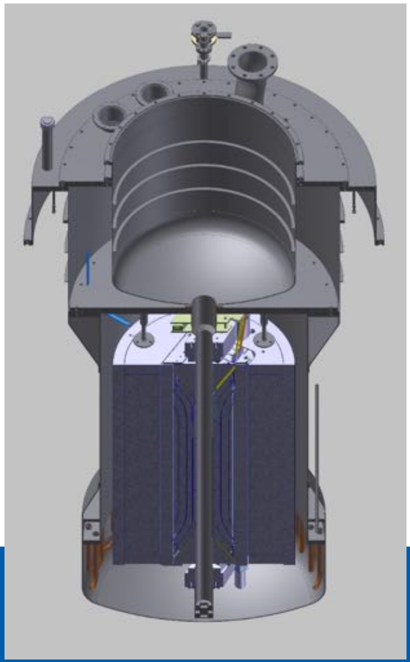
- Cables
- Model Coils
  - Short Model Coil (SMC)
  - Racetrack Model Coil (RMC)
  - Racetrack Model Magnet (RMM)
- Ultimate Nb_3Sn Dipole Models
- Value Engineered Dipole Prototype
- HTS Demonstrator Magnets

Heritage realizations

- Very High Field Test Station for high field inserts
- HTS wiggler/undulator

Cable tests

- Measurement of properties and validation of variants at cable level
  - Critical current and stability in FRESCA (FRESCA2) under relevant operation conditions, including sample preparation (resin), deformation, transverse stress and strain, joints
    - B_{peak} = 12 T (16 T)
      - L_{sample} = 2 m
      - W_{strand} ≈ 1 kg (2 kCHF)



SMC technology exploration

- The "Short Model Coil" is an intermediate step between cable and magnet, used to test rapidly technology and manufacturing variants (turnover of three months):
  - Conductor variants
  - **Insulation systems**
  - **Impregnation resins**
  - **Sliding and separating surfaces**

OD = 530 mm

L = 500 mm

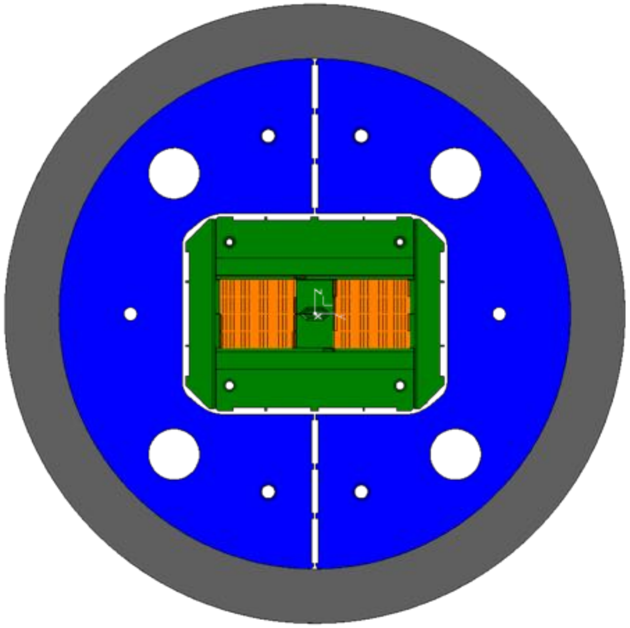
No free bore

$B_{ultimate}$ = 14 T

$W_{strand} \approx$ 10 kg (20 kCHF)

eRMC high-field operation

- The “extended Racetrack Model Coil” is a test-bed for full size conductors reproducing full field and force conditions over a representative length, including transitions, used to test manufacturing solutions:
  - **Conductor grading**
  - **Layer jumps and splices**
  - **Loading conditions**
  - Conductor interfaces to pole and end-spacers
  - Heat treatment and impregnation



OD = 800 mm

L = 1.5 m

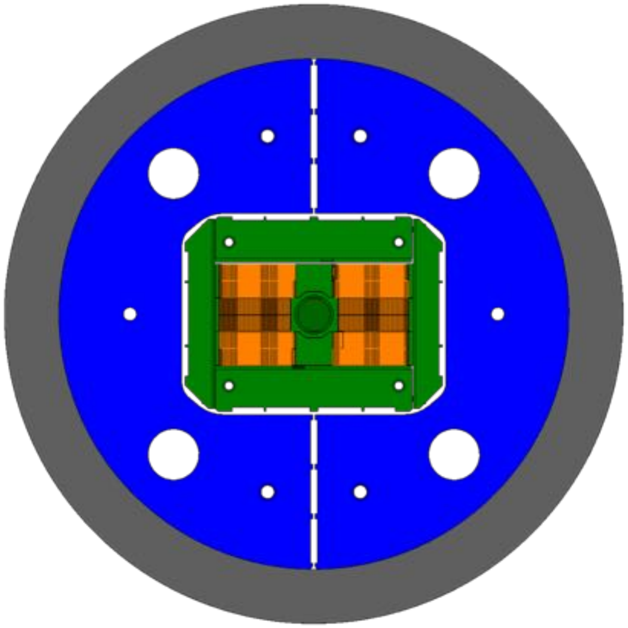
No free bore

$B_{ultimate}$ = 18 T

W_{strand} ≈ 120 kg (250 kCHF)

RMM x-section demonstration

- The “Racetrack Model Magnet” is a full size test of a block-coil magnet, including a reproduction of the 2D cross section (with a cavity, no bore), and optimized ends (0.5 T field drop) used to validate and test:
  - Force and stress management
  - **Magnet loading in 3D**
  - **Field quality in 2D**



OD = 800 mm

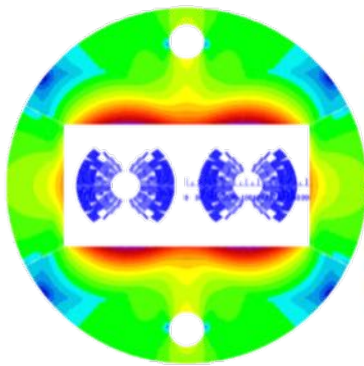
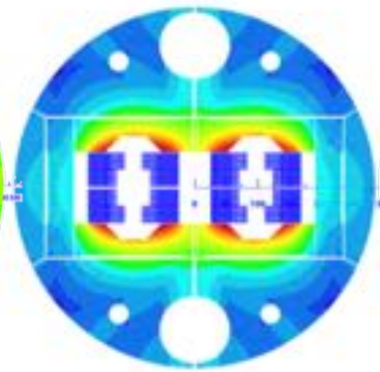
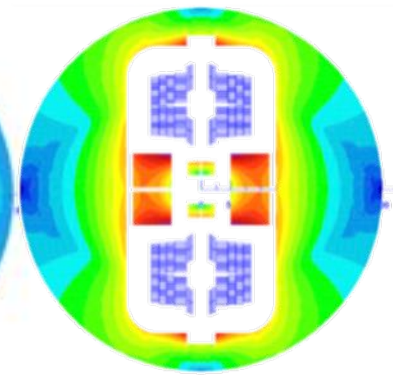
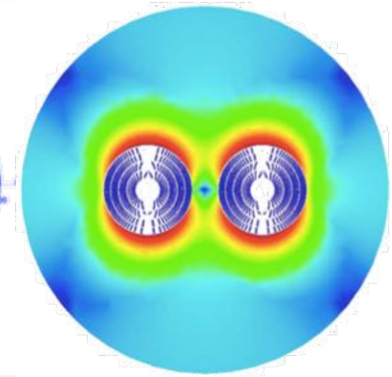
L = 1.5 m

50 mm free cavity

$B_{ultimate}$ = 18 T

$W_{strand} \approx$ 180 kg (350 kCHF)

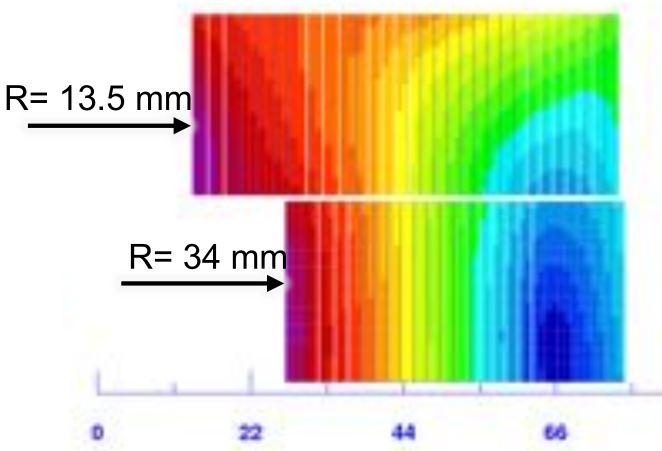
Models – 1/2

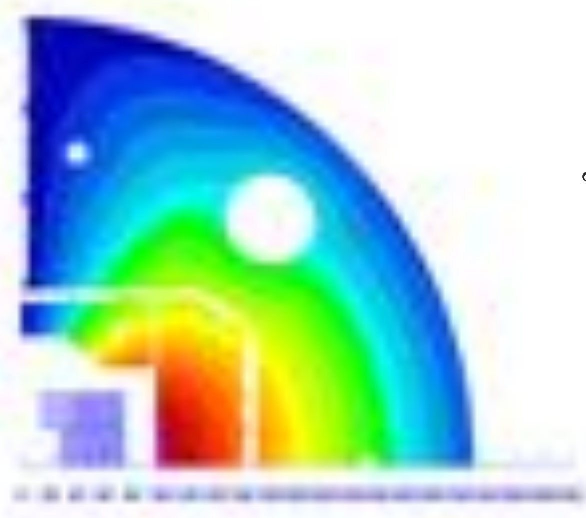





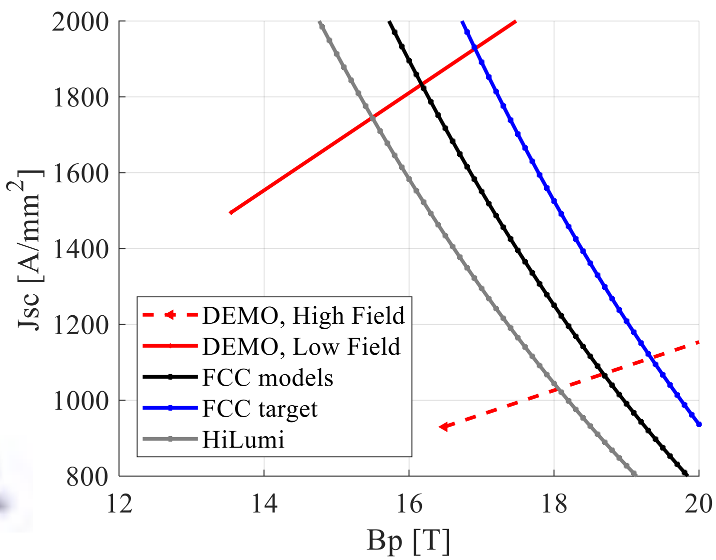
OD = 600 mm
L = 2 m
50 mm aperture
$B_{ultimate}$ = 16 T
$W_{strand} \approx$ 350 kg (700 kCHF)

		cos(θ)	blocks	common coil	CCT
Current	(A)	10000	11230	16100	18055
Inductance	(mH/m)	50	40	19.2	19.2
Stored energy	(kJ/m)	2500	2520	2490	3200
Coil mass	(tons)	7400	7400	9200	9770

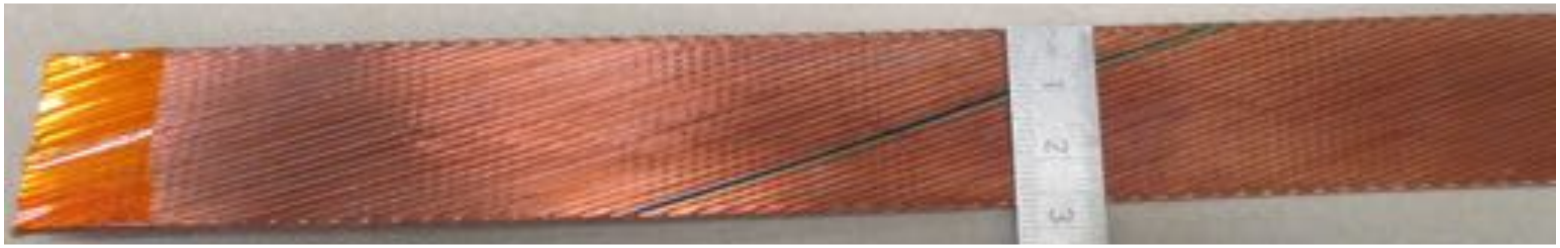
Models – 2/2





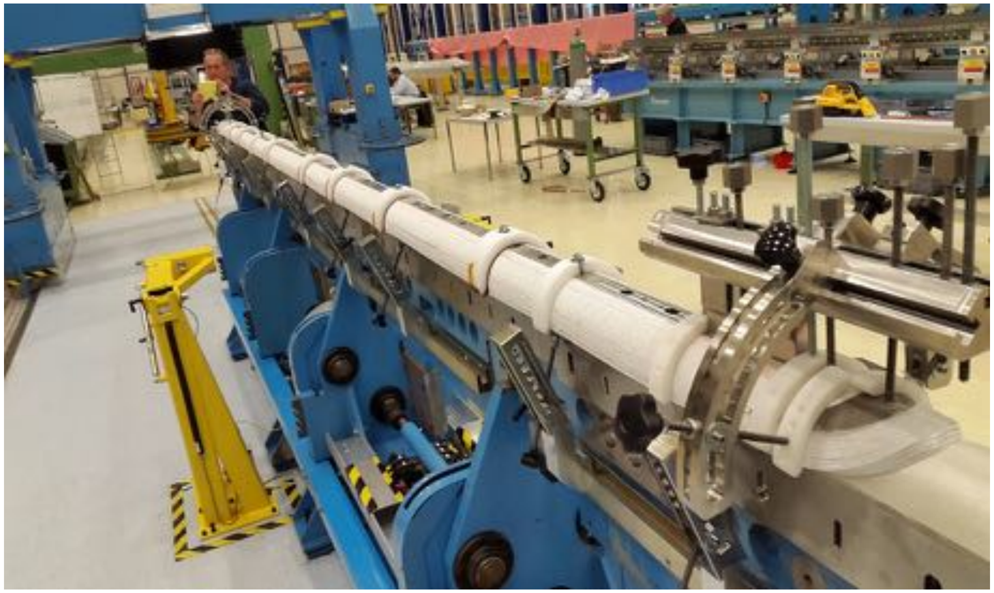


		Strands	Dstrand	CU/SC	Width	Thickness
		(-)	(mm)	-	(mm)	(mm)
Cable geometry	DEMO HF	44	1.10	0.8	25.700	2.002
	DEMO LF	56	0.85	1.2	25.700	1.547



DEMO-HF prototype
Courtesy of I. Pong
LBNL

Value Engineered Dipole



- Insulation system, fibers, sizing, binder and resins
- Coil handling (especially after heat treatment)
- Coil geometry measurement and shimming
- Splices and instrumentation
- …

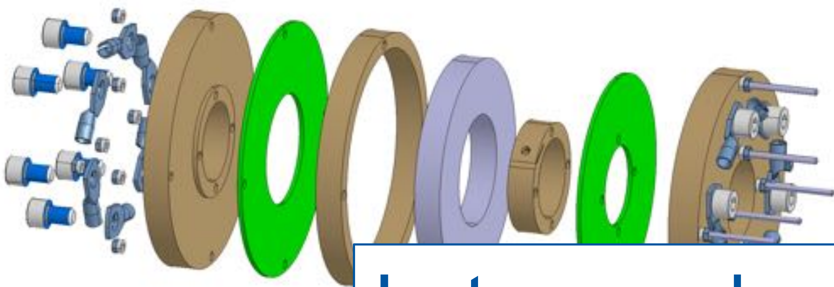
- One mold for HT and impregnation
- *Armored* coils
- Magnet assembly (collaring, bladder-and-keys, …)
- Cold mass construction
- …

Just ideas for the moment

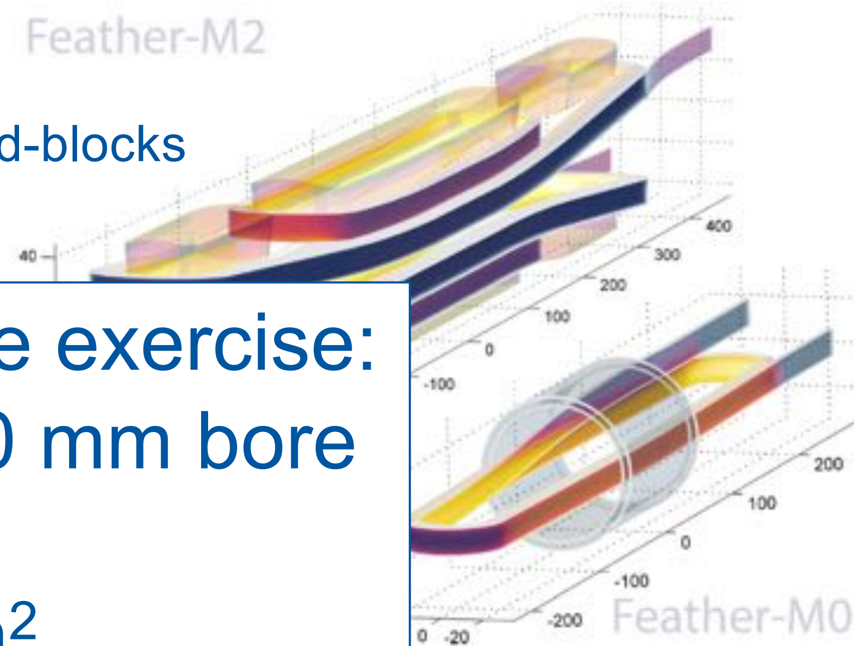
HTS demonstrator magnets

Small coils to test basic magnet properties and technology variants

Insert coils to test in-field behavior and performance reach



Aligned-blocks



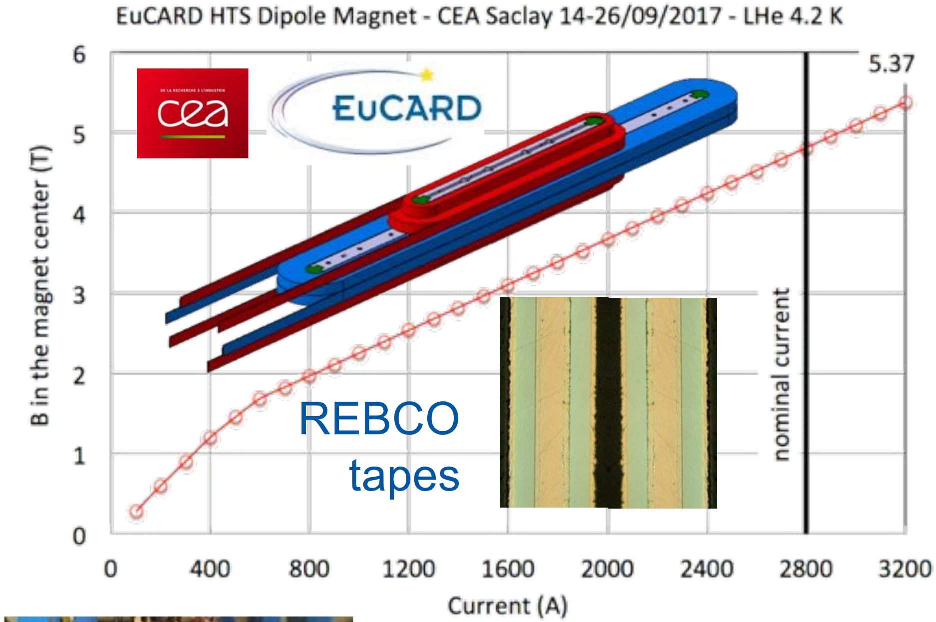
Let us make a simple exercise:
A 20 T dipole with 50 mm bore

$J_E = 600$ A/mm^2
$J_{coil} = 400$ A/mm^2
$w_{coil} = 80$ mm
$A_{coil} = 400$ mm^2
$L_{tape} = 20$ km/m
Cost : o(2 MUSD/m) ?!?

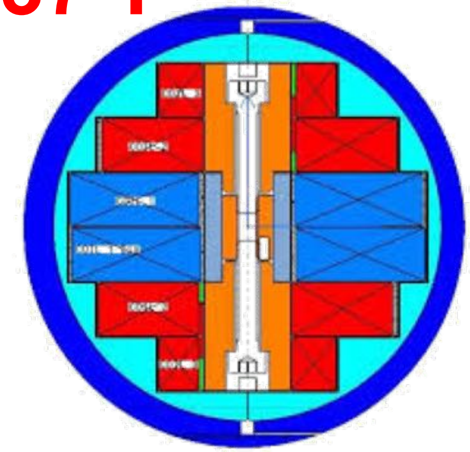
eld generated by
ather-M2 as **insert**
a magnet providing
ckground field
ESCA2 (13 T)

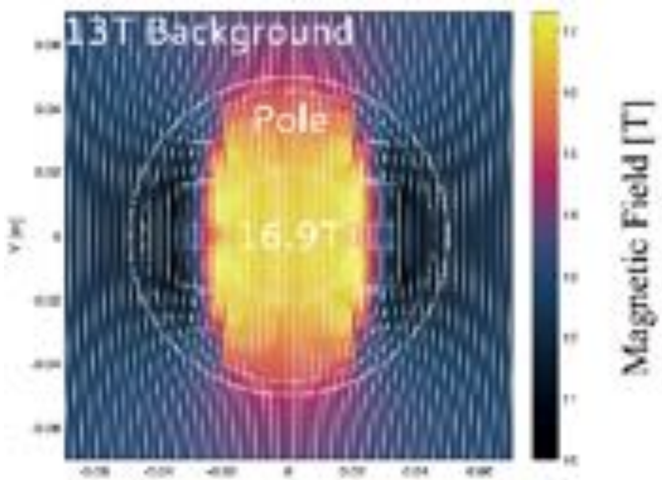
CERN

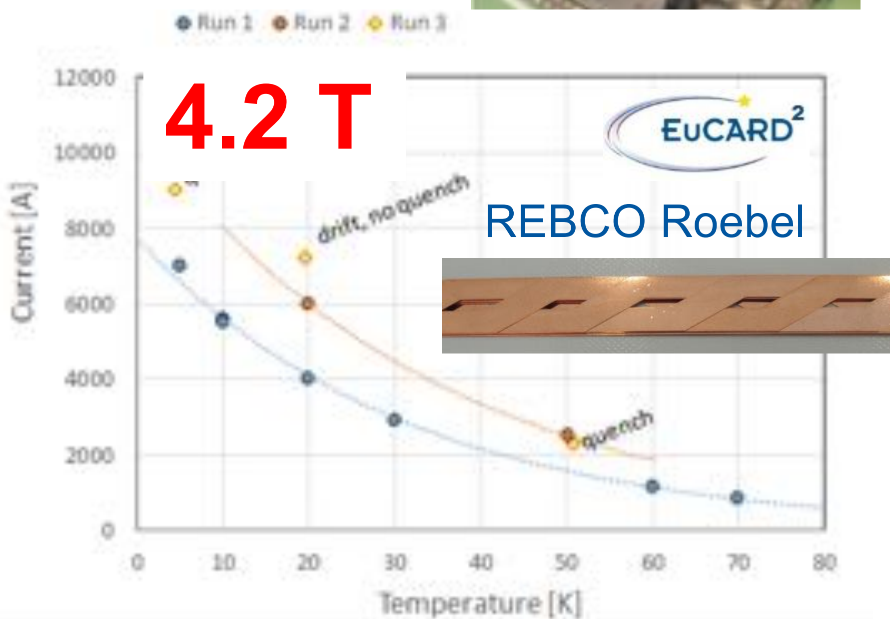
EuCARD/EuCARD^2 - HTS inserts



5.37 T







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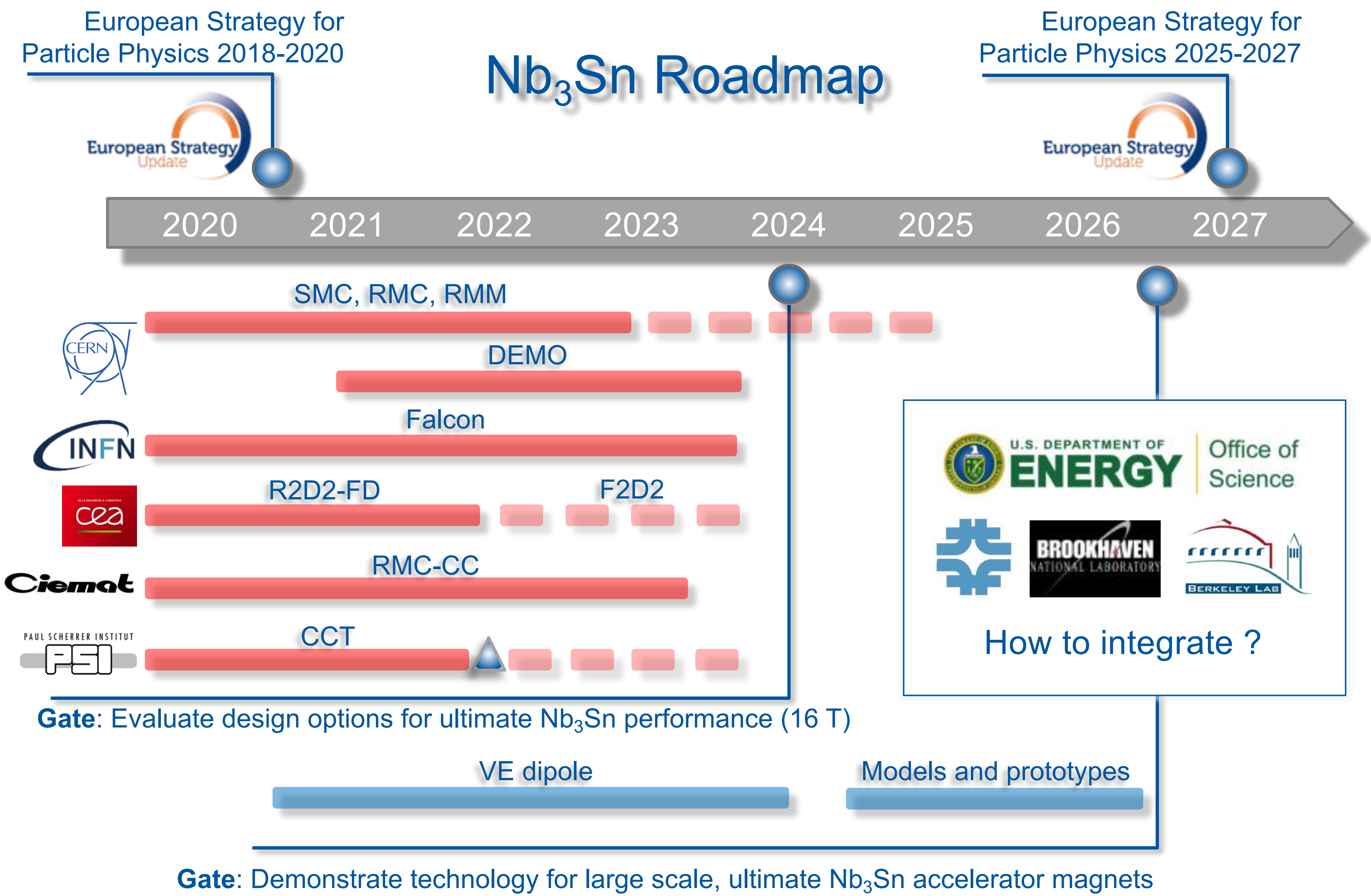
After 5 years – PROVISIONAL

- LTS program deliverables
  - Conductor R&D → HL-LHC Nb_3Sn at multiple suppliers, reduced cost. Superconductor with properties approaching FCC targets
  - Insulating materials R&D → Upgrade of the insulation scheme
  - Magnet technology R&D → An answer to basic questions on training, protection, and mechanics (SMC, eRMC, RMM). Model magnet results beyond HL-LHC (model magnet results) ready for *critical decision*
  - Accelerator magnet R&D → Engineering upgrade and optimization of design, methods, materials and tooling for large series production of long magnets, ready for long magnet prototyping
  - Infrastructure R&D → New very high-field test station
- HTS program deliverables
  - Conductor R&D → Consolidated development targets. Exploration of alternatives for materials and cables, and associated characterization
  - Coil and magnet technology R&D → exploration of basic design concepts. Coil and magnet fabrication technology. An answer to basic questions on suitability for accelerator operation (small coils, coil inserts, small models)
  - Demonstrator undulator ready for test in a beam line
- Review the High Field Magnet program at the end of this phase (Gate Review in 2024)

Nb_3Sn Roadmap



We need to develop a similar roadmap for HTS

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- Two main aims:
  - Exploit Nb_3Sn magnet technology up to its practical upper limit, both in terms of maximum performance (maximum field target 16 T) as well as scale (production in large series o(10^3) units)
  - Provide a proof-of-principle for HTS magnet technology beyond the reach of Nb_3Sn, with a target of 20 T dipole field, and sufficient field quality for accelerator application
- The program targets to reach critical results for the *next season* of the European Strategy for Particle Physics (2025-2027)
- It will be highly beneficial to integrate programs into a joint High Field Magnet Development Plan

Here Be Dragons